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Analysis and modelling of window and glazing systems energy performance for a well insulated residential building

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ABSTRACT

The energy performance of a window depends on its thermal transmittance, the glazing solar transmittance, and the air leakage due to the frame and installation airtightness.

In new installations air leakage represents a quite small term which is almost independent from the window and in particular from the glazing system selection.

The contributions of the two other terms to the building thermal balance are not independent to each other: the most effective thermal insulating glazing, as triple glazings, are generally characterized by low solar transmittance reducing solar gains. The thermal energy balance of the building is then affected not only in summer but also in winter, potentially increasing heating energy need.

This work evaluates the impact of different kinds of glazing systems (two double and two triple glazings), window size (from 16% to 41% of window to floor area ratio), orientation of the main windowed façade and internal gains on winter and summer energy need and peak loads of a well insulated residential building. The climatic data of four localities of central and southern Europe have been considered: Paris, Milan, Nice and Rome. A statistical analysis has been performed on the results in order to identify the most influencing parameters.

1. Introduction

As a consequence of the EPB Directive 2002/91/CE, many national legislations were adopted by the Member States introducing requirements imposed by law for energy saving for new and existing buildings, as for instance in Italy with the laws [1,2]. In many cases those requirements assumed the form of stronger insulation performance for all envelope building surfaces and in particular of maximum values for the thermal transmittance of the envelope components.

Italian legislation [3] acted also on the solar transmittance of glazings, intending to control the summer solar gains by giving maximum allowable solar transmittance values in absence of other solar control devices. However, solar gains can largely influence the thermal energy balance of building both in summer and winter season as emphasized by the methodology for the calculation of energy needs adopted by European Community Countries proposed by CEN standard EN ISO 13790:2007 [4].

Building designers should take into account that the most effective thermal insulating glazing systems, as the triple glazing windows, are also characterized by low solar transmittance. This could be useful to control solar gains during the summer season and to reduce cooling energy use, but in winter the reduction of solar gains can overcome the reduction of thermal losses and increase the energy needs.

Besides to solar transmittance, the size and the orientation of the windows could have a large effect on the energy use of buildings. The right design of a modern low energy building is then a careful trade-off among the properties of the different components, its collocation and its orientation. This is very important for the optimization of the solar gains.

The performances of glazing systems for different Italian climatic conditions and for different extensions of glazed area have been analyzed by the authors for office buildings [5,6]. In that case, computer simulations were performed in order to evaluate heating and cooling loads, with different window area extension, different glass types and different air flow ventilation; the simulated office building was proposed by IEA Task 27. Authors suggest to utilize

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Nomenclature

A	surface area [m^2]
CDD	equivalent cumulative degree-days [K d]
F	view factor for radiation exchange
g	glazing solar transmittance
ϕ	thermal power [W]
h	heat exchange coefficient [$W\,m^{-2}\,K^{-1}$]
H	global irradiation [MJ/m^2]
HDD	heating degree-days [K d]
I	global irradiance [W/m^2]
R	adduction surface resistance [$(m^2\,K)/W$]
R^2-adj	adjusted coefficient of determination
T	absolute temperature [K]
U	thermal transmittance [$W\,m^{-2}\,K^{-1}$]

Greek symbols

ε	emissivity
θ	temperature [°C]
σ	Stefan–Boltzmann constant (5.67×10^{-8}) [$W\,m^{-2}\,K^{-4}$]

Subscripts

C	in cooling operation
e	relative to the external ambient
f	relative to the floor area
g	relative to the glazing
H	in heating operation
i	relative to the internal ambient (temperature)
int	relative to the internal ambient (gains)
m	mean value between the air temperature and the sky fictive temperature
max	maximum value for the considered season
r	relative to the IR radiation exchange
sol	solar (heat gain)
set	of set point
sky	relative to the sky vault
sol–air	equivalent sol–air
tr	transmission (heat transfer)
W	relative to the window
$2dd$	two days moving average

low-emission glasses and to optimize the percentage of the window area depending on the climatic zone in order to optimize the specific thermal need [kWh/(m^2 year)].

Karlsson and Roos [7] emphasized the importance of the solar transmitting properties and predicted that the use of low thermal transmittance and low emittance glazings can lead to a worse performance especially in heating dominated climates and for south orientations.

Rosencrantz et al. [8] showed that an anti reflective coating significantly increases the solar and daylight transmittances of low-emissive glazings. However they found that for northern climate and quite high window transmittances, differently than for the daylight factor improvement, the reduction of thermal losses obtained by low-emissive coatings prevails on the recovery of solar gains given by the anti-reflective coating.

Persson et al. [9], analyzed the influence of window size on the energy balance of low energy houses, calculating winter and summer energy use for different orientations of a terraced passive house with triple glazings windows in the climate conditions of Gothenburg (Sweden). As regards the building orientation they found analogous trends for the winter and summer energy use, but differently from the results of the present paper, they showed a certain improvement in winter performance when reducing the window area in south orientation. This could be due to the higher opaque envelope insulation and to the particular climatic condition of Gothenburg, with lower solar radiation and lower external temperatures and to the higher set point temperature, which enhance the relevance of the window thermal losses with respect to the opaque envelope losses and to the solar gains.

Poirazis et al. [10] analyzed the effect of glazing features and surface on a large office building, simulating the energy performance with different orientations, control strategies and internal layout for the climate of Gothenburg. Eskin and Turkmen [11] calculated the effects on energy performance of parameters like the climatic conditions, insulation, thermal capacity, aspect ratio, color, shading, window systems and area, ventilation rates and control strategies for a office building in four climates in Turkey. The effects of window size and type were considered mainly for their impact on the cooling energy and peak load.

Approaching the design of a large office building in Portugal by means of a sensitivity analysis, Almeida Ferreira Tavares and Oliveira Gomes Martins [12] found that triple glazing windows do not improve so much the energy performance in winter as they do in summer.

To similar conclusions came Carriere et al. [13] considering the energy retrofit and the conservation measures implementation for a large commercial building in Saskatoon (Canada).

Urbikain and Sala [14] compared different Window Energy Rating System (WERS) in order to obtain a WERS for two climatic zones in Spain, establishing a dependence law of the useful energy for the heating system of the building in terms of the total transmittance of the window, the frame thermal transmittance, the glazing solar transmittance and the infiltration rate.

The present work is aimed to evaluate the impact of different kinds of glazing systems (two double and two triple glazings), window size (considering a range from 16% to 41% of window to floor area ratio), orientation of the principal windowed wall and internal gains on the winter and summer energy use and peak loads of a well insulated residential building. The climatic data of four localities of central and southern Europe have been considered, Paris (Trappes), Milan, Nice and Rome.

The analysis has not been extended to the lighting use, which does not seem relevant for the considered residential destination for the quite large window area of all the simulated configurations, and to the impact on the internal thermal comfort of the higher radiant temperature allowed by the more insulated glazings.

2. The building

Starting from a quite simple example of a residential building, a set of simulations has been performed to evaluate the importance on the winter and summer energy need.

The considered building is an example of a well insulated solution with an average thermal transmittance of the opaque envelope around 0.17–0.18 $W\,m^{-2}\,K^{-1}$) (Table 1). With a rectangular shape (internally 10.22 m long per 6.11 m wide), it develops on two storeys. The longer and south oriented side contains the main part of the window surface. Other 3.2 m^2 of transparent elements (the 3% on the floor area) are present only on the opposite side (north).

A constant ventilation by outside air of 0.3 air change per hour has been considered.

The study analyzes in the climatic and solar radiation conditions of Paris (for which the data of the near town of Trappes were considered), Milan, Nice and Rome, the effects of:

- four different kinds of glazing systems, two of which are double glazings and two are triple glazings, with the features indicated

Table 1
Composition of the opaque envelope.

	Thickness m	Conductivity W m^{-1} K^{-1}	Density kg m^{-3}	Specific heat J kg^{-1} K^{-1}
External wall (from inside to outside)				
Gypsum panel	0.015	0.36	1150	1100
Plywood	0.065	0.13	500	1600
Wood–fiber insulation	0.200	0.04	160	2100
Waterproof layer	0.002	0.16	300	1300
Air layer (still air)	0.030	–	1.2	–
Wood covering	0.020	0.15	600	1600
Roof				
Gypsum panel	0.015	0.360	1150	1100
Air layer (still air)	0.025	0.026	1.2	1005
Moisture barrier	0.001	0.160	300	1300
Mineral wool and wood frame	0.250	0.048	77	1400
Medium density fiberboard	0.015	0.120	600	1700
Waterproof layer	0.002	0.160	300	1300
Air layer (ventilated)	0.050	–	1.2	–
Roof tiles	0.015	0.900	2000	840
Ground floor				
Floor tiles	0.015	1.000	550	800
Lightweight concrete subfloor	0.060	1.400	2000	880
Waterproof layer	0.004	0.230	100	1410
Polystyrene	0.150	0.035	40	1600
Concrete slab	0.200	1.160	2000	920

Table 2
Features of the glazing systems.

Glazing code	Composition	Thermal transmittance W m^{-2} K^{-1}	Solar transmittance g	Spacer type
Double glazings #1	4/15/4	1.4	0.61	Aluminium
Double glazings #2	4/15/4	1.1	0.61	Aluminium
Triple glazings #3	4/16/4/16/4	0.6	0.40	Aluminium
Triple glazings #4	4/15/4/16/4	0.7	0.59	Aluminium

in Table 2, while frames are considered always the same with a thermal transmittance of 1.2 W m^{-2} K^{-1})

- four different window sizes: 16%, 25%, 34% and 41% of window to floor area (Fig. 1)
- four orientations, starting from windows mainly south oriented and considering mainly east, west and north solutions; the whole building was rotated towards the desired orientation
- two internal gain levels: without gains and with internal gains set at 4 W/m^2.

Moreover the effects of shading overhangs on the side with the main part of windows have been investigated comparing the south oriented results obtained with and without the shading of the roof and of the balcony overhangs.

The different parameters have been varied one each time in order to consider any combination of values, so 640 configurations were obtained considering the four climates. The results comprise both winter and summer energy need and winter and summer peak load.

3. Simulation method and assumptions

The building performance has been calculated by means of TRNSYS software and its multi-zone building simulation subroutine called Type 56. The simulation hypotheses are the following:

- direct and diffuse solar radiation on internal surfaces are distributed by absorptance weighted area ratios; in particular absorptance has been considered 0.6 for the floor surfaces, 0.3 for the others
- for the long wave radiation internal exchanges, view factors equal to the area fraction and black surfaces are considered
- fixed value convection coefficients are calculated from the standard EN ISO 6946:2007 [15]

Table 3
Selected independent variables and models in the regression analysis.

Variables	Unstandardized		Standardized
	Coefficients	Std. error	Coefficient
	Model: Heating energy needs [kWh/m^2]		R^2-adj = 0.932
(Constant)	8.850	1.805	–
HDD	0.023	0.323×10^{-3}	0.820
ϕ_{int}/A_f	−3.693	0.107	−0.397
I_H	−0.010	0.298×10^{-3}	−0.388
A_{int}/A_f	−0.224	0.025	−0.103
U_g	10.397	0.929	0.179
g	−32.330	3.363	−0.154
	Model: Cooling energy needs [kWh/m^2]		R^2-adj = 0.741
(Constant)	69.772	3.945	–
A_g/A_f	−1.511	0.063	−0.538
CDD	3.15×10^{-3}	0.122×10^{-3}	0.628
U_g	−21.651	2.523	−0.288
ϕ_{int}/A_f	−2.948	0.271	−0.245
g	−25.958	8.664	−0.095
	Model: Heating peak load [W/m^2]		R^2-adj = 0.892
(Constant)	4.969	0.607	–
$\theta_{sol-air,g\|min}$	−1.907	0.041	−0.675
ϕ_{int}/A_f	−0.957	0.034	−0.405
U_g	5.777	0.297	0.392
A_g/A_f	0.182	0.008	0.329
I_H	−0.001	95.5×10^{-6}	−0.152
g	−3.847	1.075	−0.072
	Model: Cooling peak load [W/m^2]		R^2-adj = 0.820
(Constant)	92.362	3.147	–
A_g/A_f	−1.903	0.053	−0.671
$\bar{\theta}_{sol-air,g}\ l\big\|_{2dd,max}$	−0.375	0.012	−0.675
U_g	−42.065	1.690	−0.554
ϕ_{int}/A_f	92.362	3.147	–

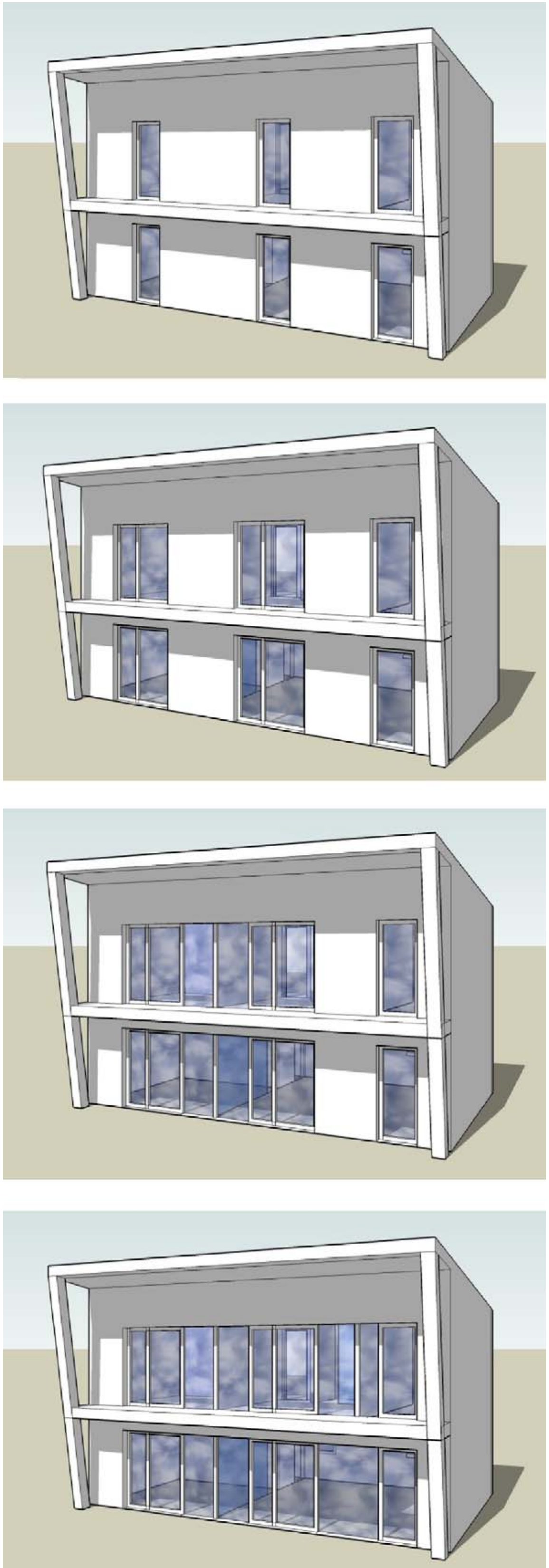

Fig. 1. The considered building in the four window configurations from 16% to 41% window to floor area.

- a ventilated air layer is considered according to the EN ISO 6946:2007 approach
- thermal bridges are considered explicitly for the corners towards external air and a C2 linear transmittance value according to the standard EN ISO 14683:2007 [16] was assumed while the thermal bridge attached to the ground floor of vertical walls (assuming a GF8 linear transmittance value) has been included in the calculation of the ground floor equivalent features
- the ground floor is considered according to the standard EN ISO 13370:2007 annex D [17]
- shading effects are accounted only on the transparent surfaces situated on the most windowed side of the building using the TRNSYS subroutine Type 34 Overhang and Wingwall; overhangs depth is considered of 1 m for the balcony over the first floor and 1,6 for the roof
- hourly climatic data were calculated from average monthly values (from the Italian Standard UNI 10349:1994 [18] for Milan and Rome and from TRY weather files [19] for Trappes and Nice) using the TRNSYS subroutine Type 54 Weather Data Generator
- heating set point was fixed at 20 °C while the cooling one at 26 °C.

4. Results and discussion

The results are shown in Figs. 2 and 3 only for the climates of Milan, which is representative of both the situations with relevant energy needs (as is the case of Paris) and the conditions with evident cooling needs (as are for instance Nizza and Rome). Trends concerning Paris, Nizza and Rome were found to be very often quite similar to these of Milan. As west and east orientation energy needs differ for less than 1 kWh/m^2 the results for those orientations are averaged. The same has been done for the peak loads although in this case the values can significantly differ in cooling operations, in particular for southern latitudes. In the most critical case of Rome, the difference between west and east cooling peak loads increases from 6 W/m^2 at 16% window surface ratio to 12 W/m^2 at 41% window surface ratio.

4.1. Winter energy need

The data show some common trends for all the considered climates. As regards the cases without internal gains, the winter energy need always decreases with increasing window area for orientations different from north. The reduction is more important for the triple glazings than for double, as for the former the increase of thermal losses is lower: the only exceptions are the case of Paris (Trappes) and Milan (Fig. 2) for orientation east or west, for very large window area and for double glazings. This behavior is enhanced and extended to the south orientation by the internal gains, which moderate the decreasing slope of all the lines. This is due to the larger relevance of thermal losses when internal gains are present.

Quite stable or increasing trends are shown for the north orientation and for the double glazings, and, when internal gains are assumed, also for triple glazings. In those cases the solar gains can only compensate but not overcome the thermal losses.

Triple glazings are the preferred choice only for the type #4, for which the solar transmittance is close to the one of the double glazings.

The south orientation for the building and, for this orientation, an increase of the window surface are the most effective expedients to reduce the winter energy need.

4.2. Summer energy need

The summer energy need increases very much while increasing window area except for the north orientation on which, as seen for winter, solar radiation is less important. Yet for Milan (Fig. 2), the

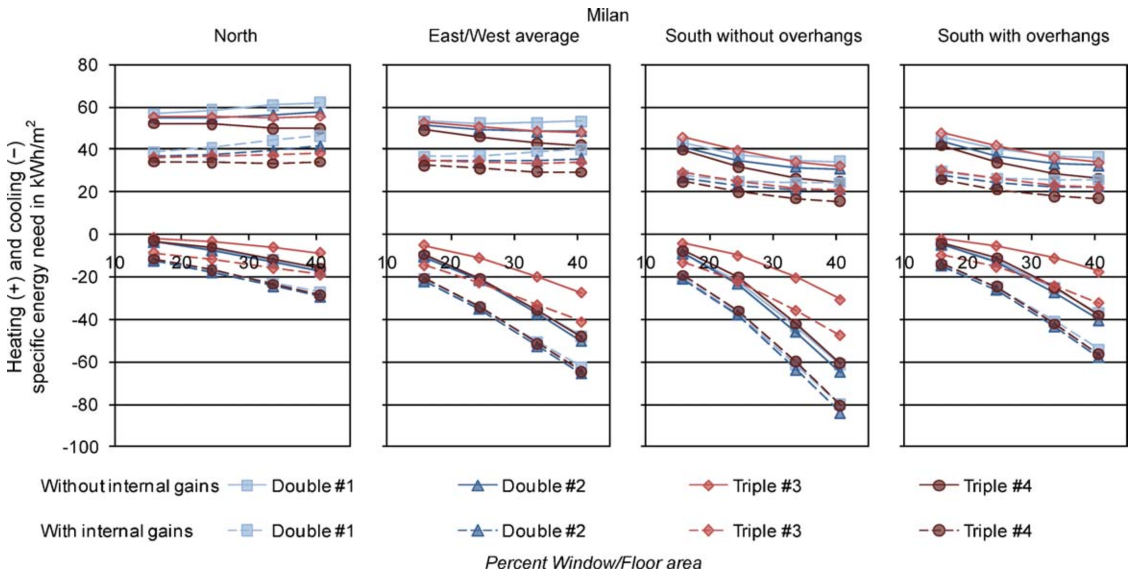

Fig. 2. Trends of heating and cooling energy need for different window to floor area ratios: Milan.

summer energy need of the considered building with internal gains becomes larger than the winter one (raising the ventilation rate or using the night ventilation would reduce the effect). The winter benefits coming from higher window area are much less than the increase of the summer energy need, that requires better control strategies for instance using night ventilation or moveable shading devices.

Triple glazings #4 behaves very closely to the double glazings #1 and #2, while the best performing is the triple glazings #3: its lower solar transmittance can neutralize the rise of summer energy need effect due to the internal gains.

Shadings on the south oriented configurations help to keep the summer energy need to the levels of the west–east orientations, while the winter energy need is only marginally affected by the roof and balcony overhangs.

4.3. Winter peak load

Winter peak loads values varies in a quite narrow range, with higher values around 20–30 W/m^2 for Paris and Milan (Fig. 3) and lower values around 15–25 W/m^2 for Nice and Rome.

For all the considered climates, the winter peak loads variation with windows percent area is very little. All localities show slightly increasing loads with windows area for the north, east and west orientation. For lower latitudes (Nice and Rome) and triple glazings peak loads tend to stay constant for any windows surface. Double glazings show a higher variation due to the higher thermal transmittance. Internal gains downshift the loads by a constant amount.

The results are coherent with the consideration that winter peak loads are more affected by the external temperature conditions and therefore by the heat losses than by the solar gains. Solar transmittance is then irrelevant in determining the peak loads as is shown by the superposition of the triple glazings #3 and triple glazings #4 results.

For the above considerations, triple glazings are always the preferred choice.

4.4. Summer peak load

Summer peak loads emphasize the summer energy need trends. First of all the values show a very wide variation between the

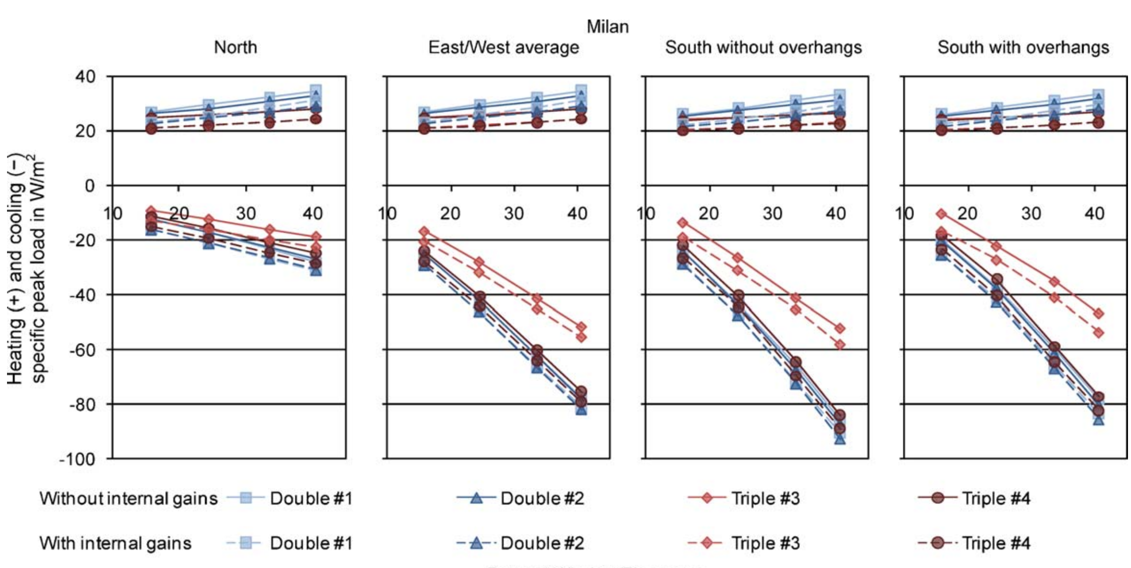

Fig. 3. Trends of heating and cooling peak loads for different window to floor area ratios: Milan.

quite null values for Paris and north orientation and values around 80–100 W/m^2 for the east, west and south orientation with double glazings or triple glazings #4.

The climate dependence is lower than the one on windows surface. Except for north orientation, peak loads tend to duplicate or more when the windows surface doubles.

Glazings with higher solar transmittance obviously show a worse behavior with higher variation due to the higher thermal transmittance.

Internal gains downshift the loads by a constant amount.

Summer peak loads are more affected by the solar gains than by the external temperature conditions and therefore by the heat losses. Thermal transmittance is then irrelevant in determining the peak loads as is shown by the superposition of the double glazings #1, double glazings #2 and triple glazings #4 results.

For the above considerations, triple glazings #3 are always the preferred choice.

5. Statistical analysis

In order to validate the information which can be derived from the whole set of data for the four considered localities, a statistical analysis has been performed. In this work, the statistical technique employed, the multiple linear regression, is not aimed to create a general model but to understand the influence of some independent variables on the heating energy needs, the heating peak load, the cooling energy needs and the cooling peak load. The selection of the independent variables has been performed with the stepwise method and each confidence interval is at 95% level. In Table 3, each variable selected is listed in order of decreasing importance on the adjusted coefficient of determination. The cases with overhangs have not been considered.

5.1. Winter and summer energy needs

In the winter case, the correlation of heating energy needs with the window features as thermal transmittance U_g and solar transmittance g, the ratio between glazing surface and floor surface A_g/A_f, the radiation received on the surface with the larger amount of glazing only in positive heating degree-hours conditions $H_{\text{sol},g,H}$, the specific internal gains ϕ_{int}/A_f, and heating degree-days HDD was investigated. Table 3 reports the selected variables, which appeared to be statistically relevant and were selected for the regression model.

During the cooling period, loads are strongly dependent on the contemporaneousness of external temperature and solar radiation. Moreover, it is impossible to know exactly if the radiation entering through the windows will cause a cooling load or not, particularly if the behavior of the other components of the building are not known.

To take into account the contemporaneous effect of the temperature and entering radiation, their values have been considered in a single variable, defined as a *modified equivalent sol–air temperature* for glazings suitable to be used for the calculations of equivalent cooling degree-hours:

$$\theta_{\text{sol-air},g} = \theta_e + \frac{gI_{\text{sol},g}}{U_g} + R_{se} \cdot h_{r,\text{sky}} \cdot (\theta_{\text{sky}} - \theta_e) \quad (1)$$

This definition has been derived from the relations used by the EN ISO 13790:2007 [4] to express the energy balance terms through the transparent components, and which can hold also in non-steady state due to the negligible heat capacity of the glazings.

The heat fluxes through the glazings are then determined as the sum of thermal losses and solar gains in the form of:

$$\begin{aligned}\phi_{\text{tr},g} = {} & \phi_{\text{sol},g} + U_g A_g(\theta_e - \theta_{i,C,\text{set}}) \\ & + [gI_{\text{sol},g} + R_{se} U_g h_{r,\text{sky}}(\theta_{\text{sky}} - \theta_e)]A_g \end{aligned} \quad (2)$$

Equating (2) to an equivalent dispersion through a glazing with the same thermal transmittance subjected to a temperature difference between the internal node and the equivalent external sol–air node in the form of

$$\phi_{\text{tr},g} + \phi_{\text{sol},g} = U_g A_g(\theta_{\text{sol-air},g} - \theta_{i,C,\text{set}}) \quad (3)$$

one can get the expression (1).

The term $h_{r,\text{sky}}$ is defined as:

$$h_{r,\text{sky}} = 4\sigma\varepsilon \cdot F_{\text{sky}} \cdot T_m^3 \quad (4)$$

where the glass emissivity ε was set to 0.837.

For the cooling energy needs analysis, the hourly differences between the internal cooling set point temperature $\theta_{i,C,\text{set}}$ and the $\theta_{\text{sol-air},g}$ have been summed all year long, only when negative and with no heating degree-hours present. The result was divided by 24 h/d to give equivalent cumulative degree-days CDD. In such a way, the radiation which is a gain in heating period has been separated from the one which could cause cooling loads in the cooling period. The other variables considered in the summer analysis are the window thermal transmittance U_g, the solar transmittance g, the internal gains ϕ_g/A_f, the ratio between glazing surface and floor surface A_g/A_f. Table 3 summarizes the ones which resulted to be statistically relevant.

5.2. Winter and summer peak loads

For winter peak loads the tested independent variables are the same as for energy needs (Table 3), except for the heating degree days that have been replaced with the minimum $\theta_{\text{sol-air},g}$ temperature.

For the summer peak load analysis, instead, to take into account of the dynamic behavior of the environment, the yearly maximum value for two days rolling-average of $\theta_{\text{sol-air},g}$ has been considered (indicated as $\bar{\theta}_{\text{sol-air},g}\big|_{2dd,\max}$). Other variables considered in the summer analysis are the window thermal transmittance U_g, the internal gains ϕ_g/A_f, the ratio between glazing surface and floor surface A_g/A_f. Table 3 summarizes the ones which resulted to be statistically relevant.

5.3. Findings

The regression analysis evidenced:

- for winter energy needs, the strong and comparable weight of thermal and solar transmittance which follows only the influence of the climatic conditions expressed by the heating degree-days, the internal gains and the solar radiation;
- for summer energy needs, the large influence of the windows area and of the contemporaneous contribution of temperature and solar radiation, which are accounted in the CDD parameter;
- for winter peak loads the project conditions (i.e., minimum sol–air glazing temperature), internal gains, thermal transmittance and windows area are the most influencing variables, while the solar transmittance effect is modest;
- for summer peak loads, the large influence of the windows area, of the contemporaneous effect of temperature and solar radiation and of the thermal transmittance.

It should be noted that the effect of the variable g is in part accounted in its interaction with I, within the $\theta_{\text{sol-air},g}$ definition.

In Figs. 4–7 the values obtained with the regression models are compared to the ones calculated by TRNSYS. In winter conditions, the points are well aligned and the majority of them are included between the two dotted lines which represent a deviation of 20%

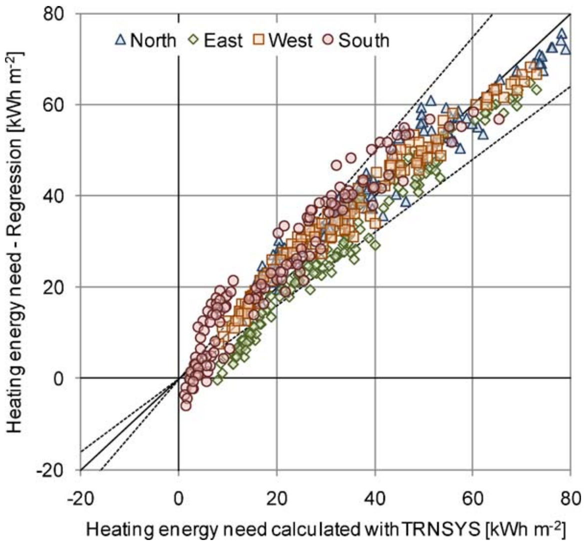

Fig. 4. Regression model for the heating energy needs.

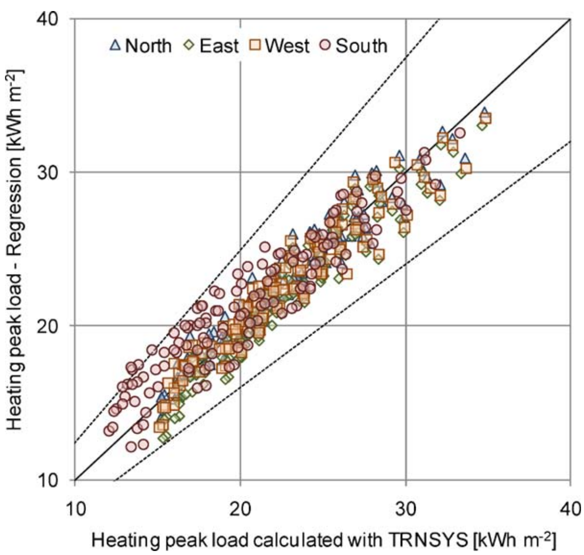

Fig. 5. Regression model for the heating peak loads.

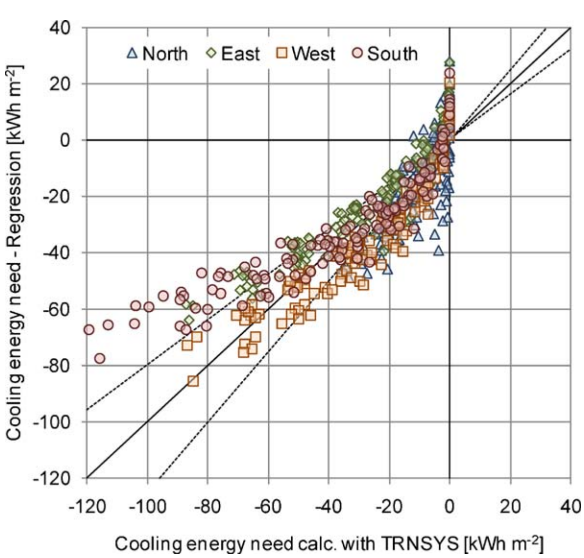

Fig. 6. Regression model for the cooling energy needs.

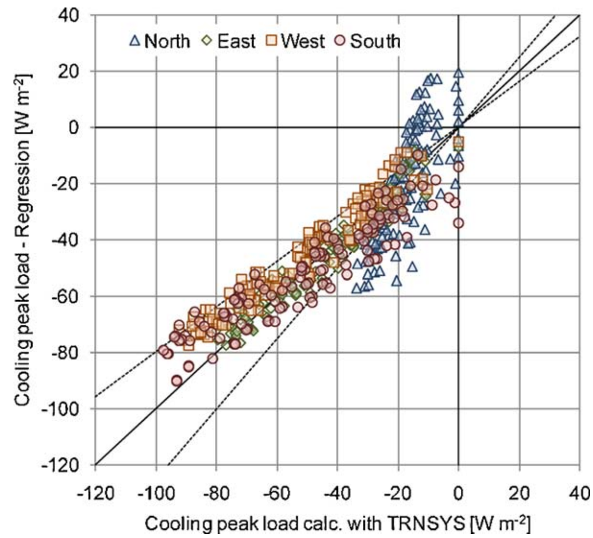

Fig. 7. Regression model for the cooling peak loads.

from the middle values. In winter energy needs calculations the worst data fit is due by south orientation and low energy demand.

About summer needs, the correspondence is not so good. In part this can depend on the description of the environment: in the definition of the parameter CDD all the radiation not involved in the winter heating balance has been considered. With a detailed balance, only the radiation responsible for cooling load could be identified in order to get a better model. Also the envelope heat capacity variation with the window to floor area should be accounted for a possible improvement of the model.

In cooling energy needs and peak loads, the different behaviors of the north oriented glazings can be underlined. This is probably due to a different weight and composition of the radiation component on this orientation.

6. Conclusions

It is possible to summarize the above results as follows:

- the use of large glazings enhances winter performance but worsens slightly the peak of winter loads (the adoption of shutters for night hours could limit this problem);
- there is an improved effect for the south orientation, which is the best performing in winter;
- in winter the use of windows with low thermal transmittance is useful if accompanied by high solar transmittance;
- however higher solar transmittance considerably worsens summer performance;
- selective shading systems should then be installed to improve summer performance without affecting the winter one.

According to the regression analysis, the thermal transmittance is relevant in winter and summer conditions both for energy and peak loads. The solar transmittance appears to be more important for winter and summer energy needs and for summer peak loads.

As a consequence of the results obtained from the computer simulations on the utilized buildings typologies, it is important to propose preliminary optimization of the solar exposition, the geometry and of the solar and thermal properties of the glazing system.

The windows surface appears to be of minor importance for winter energy needs.

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